Addressing the Ultra-Central Puzzle with Initial-State Nuclear Structures

Qi Wang[1] Long-Gang Pang[1,*] Xin-Nian Wang[1,*]

[1]Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China

Abstract

Hydrodynamic models fail to describe the near-equal v_2/v_3 ratio observed in ultra-central heavy-ion collisions, despite their success in other centrality classes. This discrepancy stems from shear viscosity suppressing higher-order geometric eccentricities, resulting in underestimated v_3.

We explore two initial-state modifications using **TRENTo** and **CLVisc**:

1. Enforcing a **minimum nucleon separation distance** ($d_{\min}$) to homogenize distributions.
2. Amplifying **sub-nucleon structures** to reduce initial eccentricity.

Both approaches significantly lower geometric eccentricity and narrow the v_2–v_3 gap, implicating initial-state nuclear structures as critical factors in resolving this puzzle.

Background & Methods

Motivation Hydrodynamic models systematically overpredict the v_2/v_3 ratio in ultra-central (0-1 %) collisions.

Hypothesis Short-range nucleon correlations and sub-nucleonic density fluctuations critically shape the initial transverse geometry.

Framework
- **Initial State:** TRENTo model (entropy density profiles).
- **Hydrodynamics:** CLVisc (3+1D viscous evolution).

Modifications
- **Min. Separation** ($d_{\min}$)**:** Leads to more uniform nucleon distribution, reducing fluctuations.
- **Sub-Nucleonic Hotspots:** Alters fine structure of energy deposition.

Uniformity of Nucleon Distribution

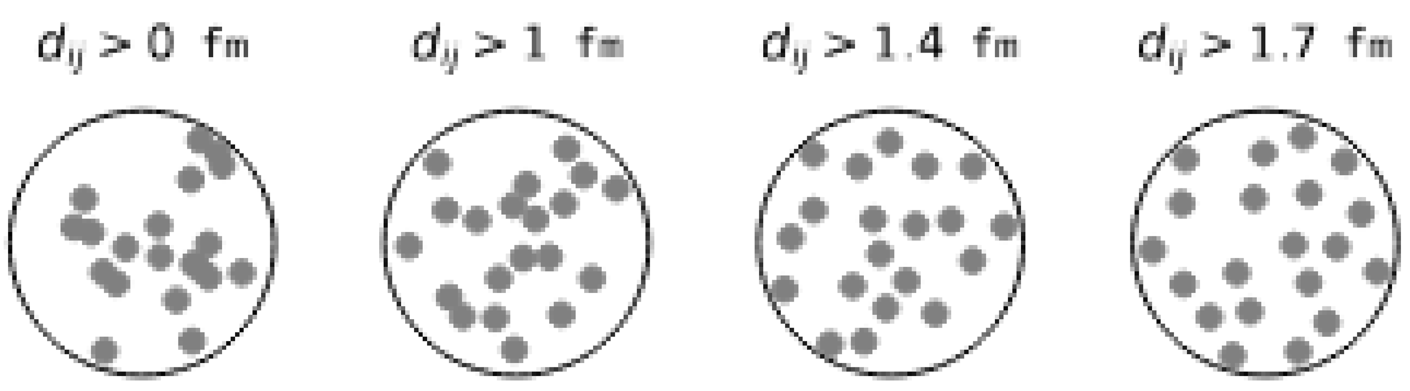

Figure 1. Schematic illustrating the relationship between nucleon distribution uniformity and minimum internucleon distance.

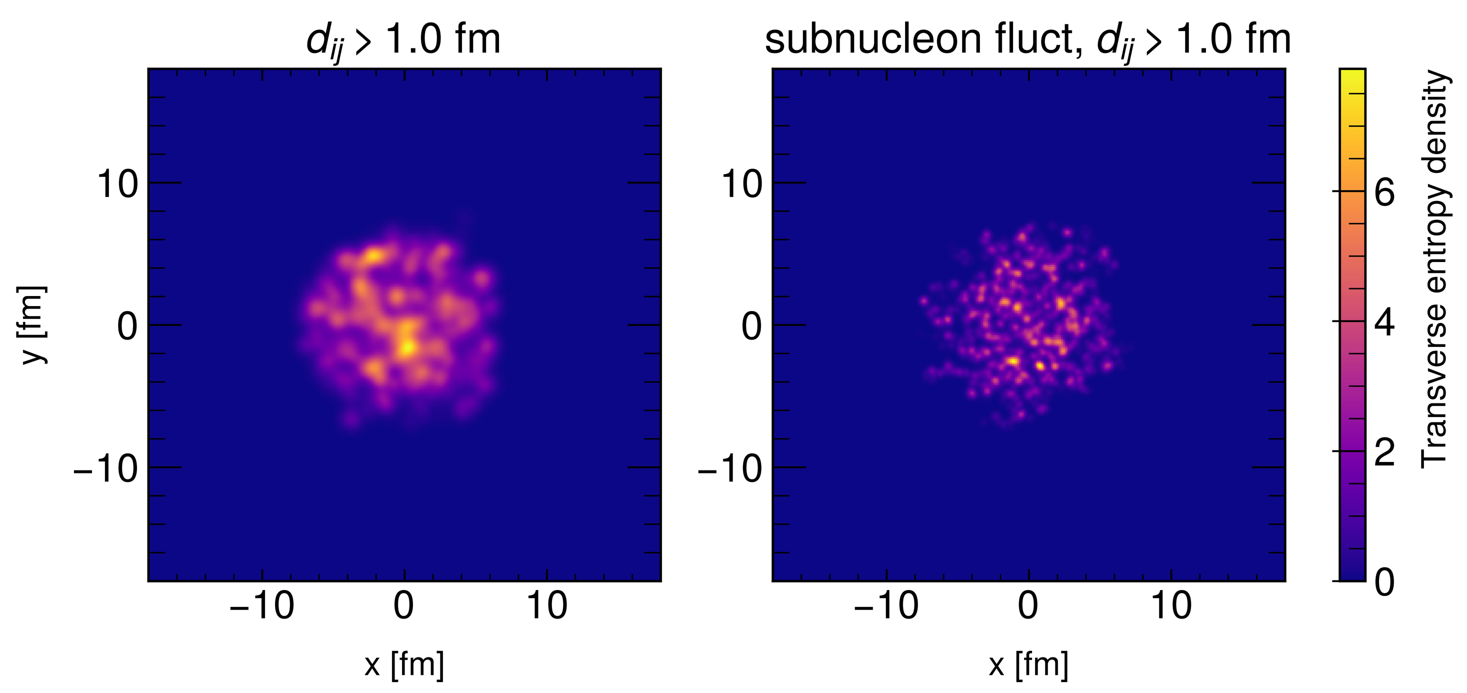

Figure 2. Initial entropy density distribution in the transverse plane for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, comparing scenarios with and without sub-nucleon fluctuations.

Initial State Eccentricities

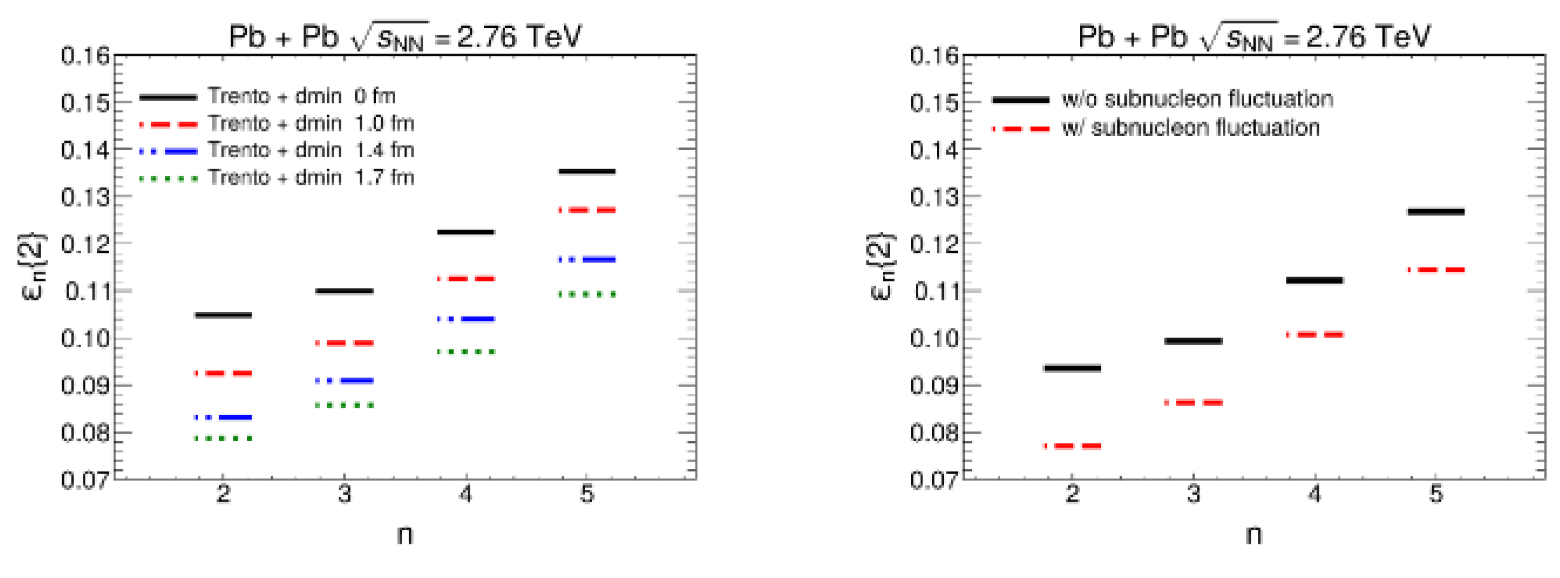

Figure 3. RMS eccentricities $\epsilon_n\{2\}$ from TRENTo model. *Left:* Variation with minimum nucleon distance $d_{\min}$. *Right:* Sensitivity to sub-nucleonic fluctuation scale (hotspot size).

Flow Harmonic Coefficients: TRENTo + CLVisc

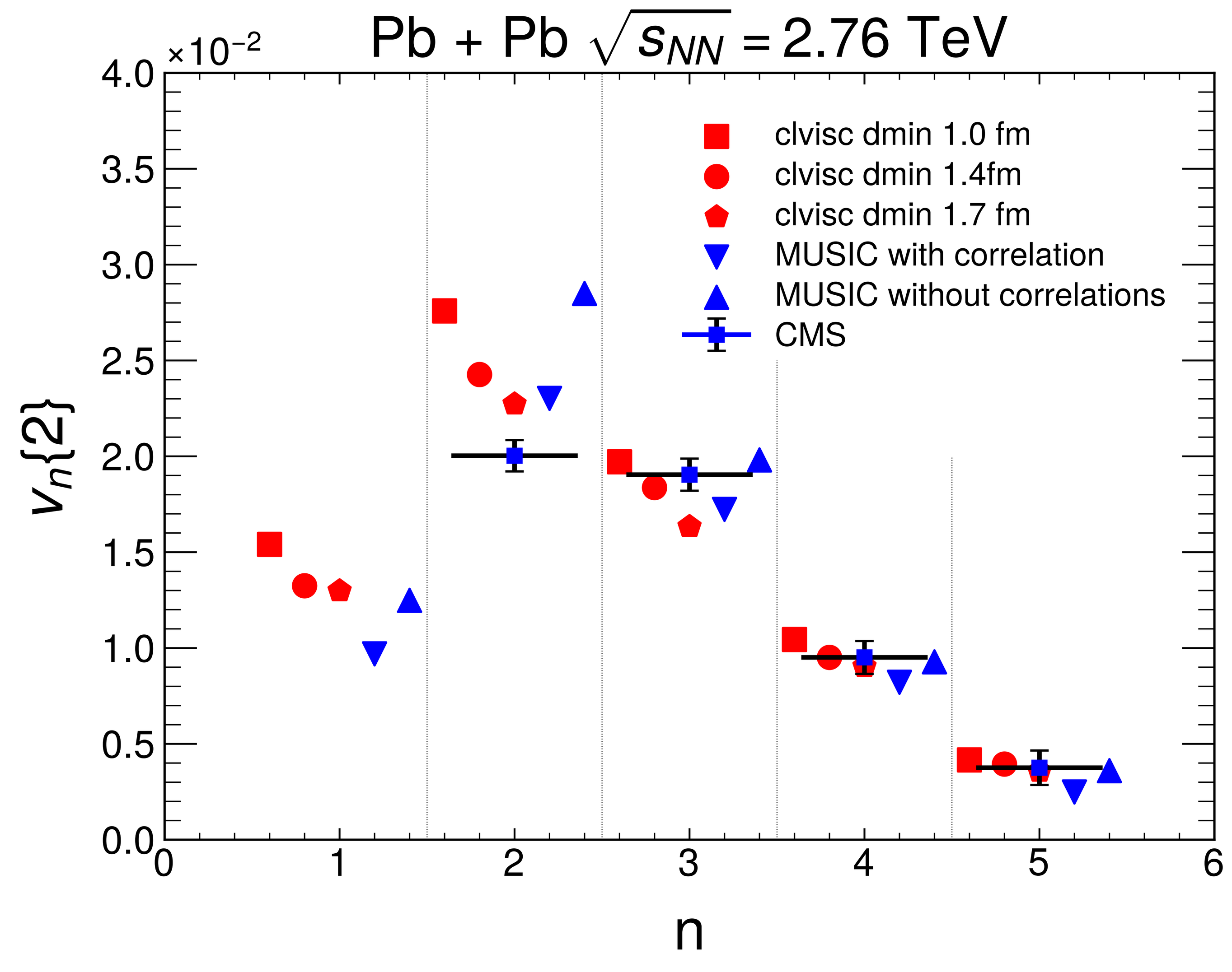

Figure 4. Flow harmonics $v_n\{2\}$. **Red:** TRENTo+CLVisc with $d_{\min} = \{1.0, 1.4, 1.7\}$ fm. **Blue:** IP-Glasma+MUSIC without/with nucleon correlations [1].

Centrality Dependence of Flow

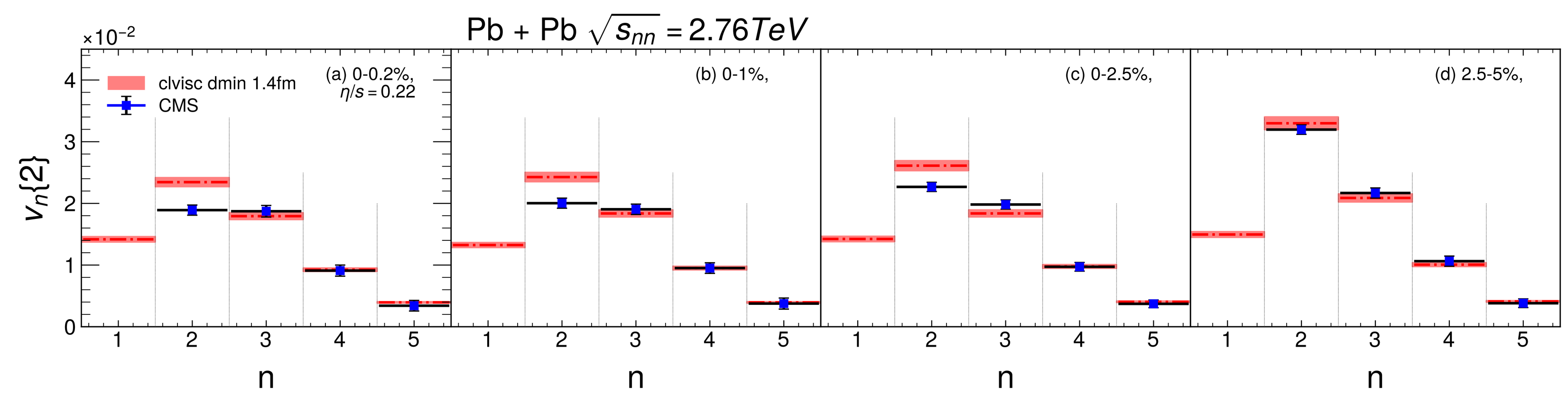

Figure 5. Centrality dependence of $v_n\{2\}$ from TRENTo+CLVisc ($\eta/s = 0.22$) compared to CMS data [2]. The red line indicates $d_{\min} = 1.4$ fm. Error bands represent theoretical statistical uncertainty.

Impact of Sub-Nucleon Structure

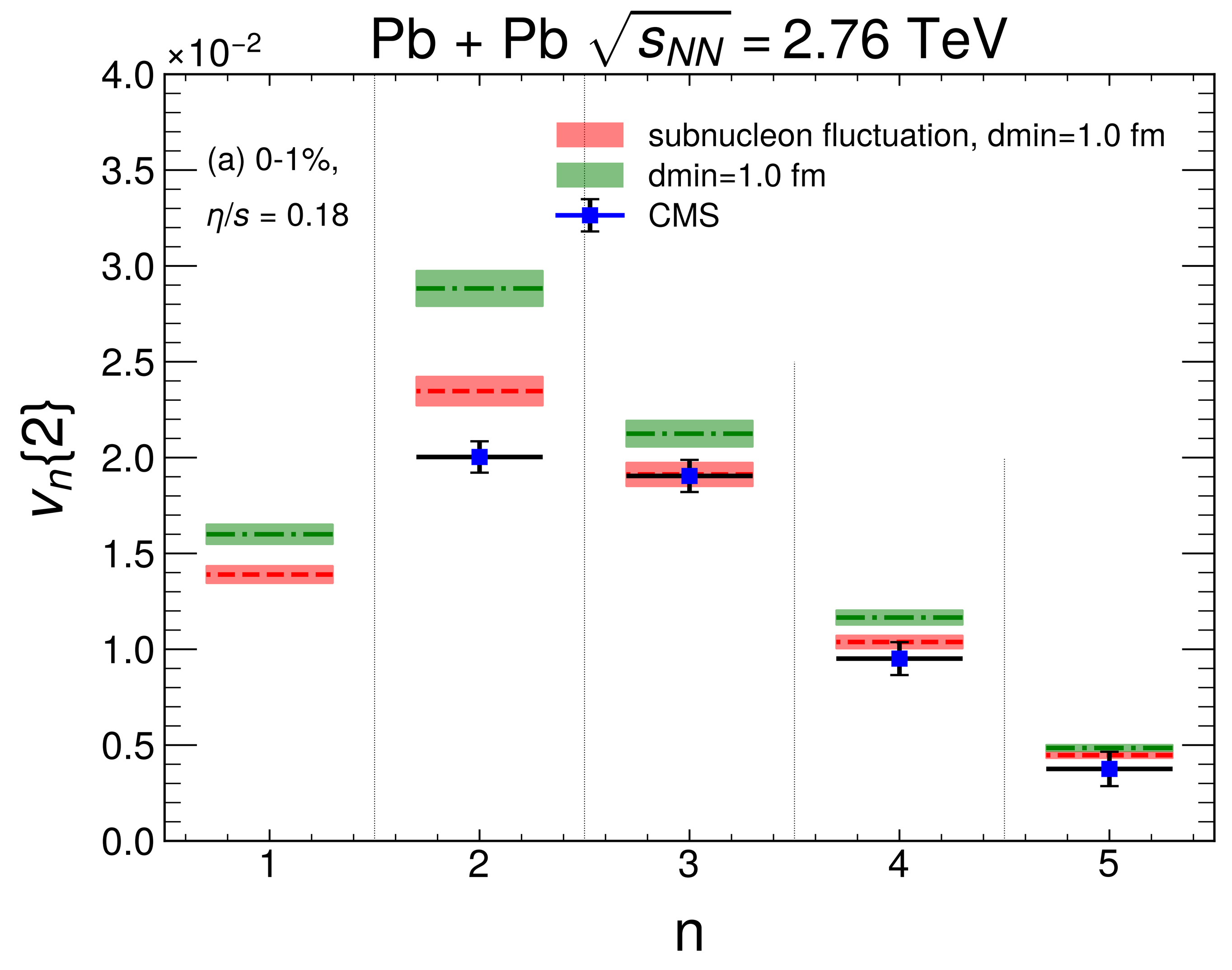

Figure 6. Comparison of $v_n\{2\}$. **Red markers:** Standard $d_{\min} = 1.0$ fm. **Red shaded:** $d_{\min} = 1.0$ fm + sub-nucleonic fluctuations ($\eta/s = 0.18$). Note the reduction in viscosity required to match data.

Summary & Conclusions

- **Spatial Uniformity:** Introducing a finite nucleon separation ($d_{\min}$) or explicit sub-nucleonic structure effectively reduces initial state eccentricities (ϵ_n).
- **Mitigating the Discrepancy:** The ultra-central v_2/v_3 ratio is highly sensitive to detailed nuclear geometry at sub-nucleonic scales. Our modifications successfully narrow the gap.
- **Precision Physics:** Accounting for these initial-state effects allows for:
  - Reconciliation of hydrodynamic predictions with experimental data.
  - More precise extraction of QGP transport coefficients (e.g., $\eta/s \approx 0.18$ with sub-structure vs 0.22 without).

References

[1] G. S. Denicol, C. Gale, S. Jeon, J. F. Paquet, and B. Schenke, "Effect of initial-state nucleon-nucleon correlations on collective flow in ultra-central heavy-ion collisions," 6 2014.

[2] S. Chatrchyan *et al.*, "Studies of Azimuthal Dihadron Correlations in Ultra-Central PbPb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV," *JHEP*, vol. 02, p. 088, 2014.